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MODEL TESTS OF A WING-DUCT SYSTEM FOR AUXILIARY AIR SUPPLY

By David Biermann and Blake W. Corson, Jr.
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INTRODUCTION

During the spring and summer of 1939 the NACA conducted for the Bureau of Aeronautics, Navy Department, a series of tests to determine the general aerodynamic characteristics of an airplane model. These tests included a fairly complete study of the cooling system intended for the Pratt & Whitney R-2800 engine equipped with a geared two-stage supercharger.

The cooling system embodied a conventional NACA cowling for the cylinder cooling and a novel wing-duct system for the carburetor air, oil coolers, and intercoolers. The airplane has since been built and the cooling system has been reported to function satisfactorily. In view of the successful operation of this design, it is believed that the description of the wind-tunnel tests should be made available to the aviation industry as a whole in order that they may benefit by the experience gained in the development of this wing-duct system. Consequently, the most interesting results from the original test data, covering only the wing-duct system, have been selected and are given in this report.

DESCRIPTION OF MODEL AND APPARATUS

The tests reported herein were conducted in the NACA 20-foot propeller-research tunnel.

Airplane model.- These tests were made on the 1/2.75 scale model of a low-wing single-engine combat airplane pictured in figure 1. The engine cowling was of circular cross section in the vicinity of the cylinders. The wing-root section was the NACA 23018; the actual maximum thickness was about 0.36 engine diameter. The duct entrances were located in the leading edge of the wing and the ducts extended back to the 30-percent chord station. The radial distance from thrust axis to the center of the duct entrance was about 0.29 propeller diameter. Distance from propeller disk aft to the duct entrance was 0.37 times propeller diameter. The diameter of the model propeller was 4.82 feet, being three times that of the engine.

Wing ducts.- Three different sets of wing ducts were tested with this model, the first being the "original ducts" delivered with the model. A picture of these ducts is shown in figure 2 and a sketch in figure 3. These ducts faired nicely into the contour of the wing root. The upper lip extended almost to the leading edge of the wing. The lower lip was considerably aft of the wing leading edge. At the section of least area the combined entrance area of the ducts was 34 square inches. A short diffuser extended from the entrance into the hollow wing. The diffuser expansion ratio was about one and a half. Space was left between the end of the diffuser and the front spar to allow air to flow into the hollow wing chamber surrounding the diffuser. From this chamber air flowed through round-edge orifices simulating oil coolers and intercoolers, into the accessory compartment, whence it was expelled into the air stream through an exit slot in the lower part of the accessory compartment. Control of the cooling air was by means of an exit flap located behind the engine cowl flaps. Air flowing from the wing chamber into the supercharger intake orifice was ejected through exhaust ports. No turning vanes were provided within the ducts. Performance of these ducts was generally unsatisfactory as will be noted later.

The "first modified ducts" represent the earliest attempt to correct the faults in the original ducts. These ducts are pictured in figure 4 and shown sketched in figure 5. The first modified ducts, like the original ducts, faired well into the wing; but the entrance lips protruded slightly above and below the leading edge of the wing. The entrance area was 34 square inches. The entire interior of the duct acted as a diffuser. Part of the diffuser extended from the duct entrance aft to a set of turning vanes located on a diagonal line from wing spar to leading edge. The region between turning vanes and orifice plate (intercoolers and oil coolers) comprised the remainder of the diffuser. Reference 2 is an exposition of the principles involved in the design of the ducts.

Although the first modified ducts functioned fairly well as air inlets, they precipitated an early wing stall so had to be altered.

In the "final modified ducts" pictured in figure 6 and shown sketched in figure 7, the upper lip was brought within the outlines of the original wing in order to correct the fault of the first modified ducts, viz, early stall. The under lip was lowered more than that of the first modified ducts and was adjustable so that two entrance areas could be investigated. The ducts were tested with entrance areas of 36 and 28.6 square inches (total area for both ducts). The internal shape of the ducts was also altered somewhat as may be noted from the sketches. The round-edge orifices, which represented the coolers, were replaced with wire screen covering the same area as the coolers so that the diffusion properties of full-scale ducts could be simulated. A calibration of the screens indicated that their conductivity was 92 percent of the desired value.

Propeller.- The propeller used in these tests was a three-blade Hamilton Standard C-Y 6159-A of 4.82-feet diameter. This was driven by a 25-horsepower electric motor.

TESTS

The original wind-tunnel tests on this model were of considerable scope; those reported here deal only with development of the wing ducts. Of primary interest was the effectiveness of the ducts as air inlets. Of secondary interest, but of equal importance, was the influence of the wing ducts on the aerodynamic behavior of the airplane as a whole. With all three sets of wing ducts, and with ducts removed and wing smooth, lift measurements were made over an angle-of-attack range which went beyond the angle for maximum lift. Drag measurements included: drag of model without ducts and wing smooth; drag of model with ducts installed and air passages blocked internally; and drag of model with ducts open and air flowing.

Pressures measured were: total pressure at the duct entrance, total pressure on the upstream side of the oil cooler and intercooler restrictions, and static (total) pressure on the downstream side in the accessory compartment. During the tests with propeller removed, pressures were measured at a series of angles of attack. With propeller operating, the angle of attack was held constant while readings were taken at a series of (V/nD) values from zero to (V/nD) of zero thrust. Tests were made with exit flap openings of 0°, 10°, and 18.5°; and propeller blade angles of 30° and 40° at the three-quarter radius.

The tests were conducted at a tunnel speed of about 100 miles per hour.

RESULTS

The following symbols and definitions have been used in presenting the results.

S wing area, square feet

ρ air density, slugs per cubic foot

V velocity of air stream (speed of flight)

q dynamic pressure $= \frac{1}{2} \rho V^2$

D drag (symbol not used in report)

C_D drag coefficient $= D/qS$

L lift

C_L lift coefficient $= L/qS$

α angle of attack of thrust line (angle of attack of wing $= \alpha + 2° 10'$).

D propeller diameter

n propeller shaft speed, revolutions per second

p pressure, pounds per square foot

P_R total pressure at entrance of starboard duct

P_L total pressure at entrance of port duct

4.

ΔP_{2R} total pressure loss in diffuser of starboard duct

ΔP_{2L} total pressure loss in diffuser of port duct

ΔP_{4R} total pressure drop across intercooler and oil cooler, starboard duct

ΔP_{4L} total pressure drop across intercooler and oil cooler, port duct

The form drag and cooling drag of the various ducts and the drag of the cowling exit flaps are shown in figures 8 to 12. The effect of the ducts on lift is given in figure 13. All other charts deal with pressures in the auxiliary cooling system. Pressures with original ducts are given in figures 14 and 15 and with the first modified ducts in figures 16 and 17. Figures 18 to 30 deal with pressures obtained with the final modified ducts. Specific curves from the above figures are given in figures 31 to 36 to show comparison between the three types of ducts.

DISCUSSION

A good cooling system should have the following properties:

(a) Low drag

(b) No effect on the maximum lift of wing

(c) Be unaffected by normal changes in the attitude of the airplane and flight speeds

(d) Low internal energy losses

(e) A pressure available at the coolers and carburetor entrance as high as possible (over q if possible)

The results of the present investigation have been analyzed on the bases of these criterions and listed in the order named.

In figures 8 to 12 are plots of the drag of the model

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with the three entrance ducts installed. It may be noted that the drag of the model with ducts removed was different for the three test conditions, which may be accounted for by differences in other parts of the model which prevailed at the time of the tests. The drag added by the ducts is in true perspective, however. The original ducts, with air flowing, increased the drag of the airplane about 13 percent at an angle of attack of -1°, which corresponds to the high-speed condition of the airplane. This high drag is attributed to the recessive lower lip which allows air to spill out at the high-speed flight condition. The first modified ducts had a slightly lower drag even though more cooling air was flowing through the ducts, as will be noted later. The final modified ducts increased the drag of the airplane 2 or 3 percent for the 36-square-inch entrance openings and about 5 percent for the 28.6-square-inch entrances. Although the protruding lower lip is not conducive to the lowest possible drag, it represents a satisfactory arrangement for this airplane.

Figure 12 shows the increase in drag resulting from opening the controllable exit flap to increase the air flow for the climb condition. The large increase in drag associated with increasing exit-flap angle illustrates the necessity for properly designing the exit and controlling the flow quantity for the high-speed condition.

In figure 13 is shown the effect of the first modified ducts on the lift, which was to cause an early stall due to the small-radius upper lips. It is quite likely that this fault could have been remedied by increasing the lip radius had the defect been known soon enough. Unfortunately, the model was removed from the tunnel before the duct characteristics were known; so no opportunity was available at the time for eliminating the trouble. When the model was put back in the tunnel at a later date, it was decided to install new ducts which were definitely known to be good from the standpoint of stalling rather than take a chance on removing the defect, even though the latter course necessitated lowering the bottom lips more than good practice seemed to allow from the standpoint of drag. (See reference 1 for drag results of different entrance types.)

The pressure characteristics of the original ducts for the condition without the propeller are given in figure 14; and with the propeller, in figure 15. The front pressures P_R and P_L reach a value of q only through an angle-of-attack range from 4° to the stall. At the high-speed condition ($\alpha = -1^\circ$) only 0.5 or 0.6 of dynamic pressure was available, which indicates that the entrance was no longer at the stagnation point. The propeller made the condition even worse because the slipstream rotation effectively decreased the angle of attack of the right wing root (see fig. 15), although the condition for the left duct was improved.

The duct internal pressure loss ΔP_2 was relatively high, amounting to over 0.2q for the useful flight range. Consequently, pressure available for cooling purposes was low, amounting to 0.1q or less. Negative pressures were recorded for the right duct when the propeller was operating, indicating the flow was leaving by way of the duct entrance instead of entering.

The pressures for the first modified ducts are presented in figures 16 and 17. It is apparent that at attitudes for high speed, cruising, and slight climb practically full dynamic pressure was available at the duct entrances and that the pressure loss within the ducts was only about 0.1q. Premature separation of flow from the duct upper lip is indicated by the duct entrance pressure curve as well as by the lift curve. Pressure characteristics of the first modified ducts with propeller operating were fairly good. The pressures in both ducts were almost identical. The influence of the propeller on the pressures available on the ground and at low V/nD was especially favorable, as indicated by the excess of entrance pressures over the dynamic pressure (p = q, curve).

Figures 18 and 19 present the pressure data for the final modified ducts with 36-square-inch entrance area. The total pressure available at the entrances was practically full dynamic pressure over the entire range of angle of attack at which prolonged operation might occur. At the attitude for high speed the pressure loss in the ducts was of the order of 0.03q. The duct losses increased somewhat at the climbing angles which apparently resulted in lower pressure drops across the coolers.

With propeller operating at low V/nD, the beneficial effect of the slipstream was somewhat more pronounced on the port duct than on the starboard duct, but was large for both. At high values of V/nD both ducts were affected equally. The pressure loss within the ducts remained about constant with changes in V/nD and amounted to only about 0.02q for the high-speed condition. The pressure available for cooling for the high-speed condition appears to be somewhat greater than that required, a condition that is easily remedied by increasing the restriction at the exit slot.

The cooling data for the 36-square-inch openings and for condition with flap set 10° and 18.5° are given in figures 20 to 23. The only important effect of opening the flap was to increase the pressure available for cooling. The cooling pressure drop, ΔP_4, ranged from about 2q to 1.2q for the climbing values of V/nD from 0.5 to 0.8. (See fig. 23.)

The pressure characteristics for the 28.5-square-inch ducts are given in figures 24 to 29. The only noticeable effect of reducing the size of the entrance openings was to increase the internal losses slightly at the expense of the cooling pressure drop.

In figure 30 is shown the effect of deflecting the wing flaps to 50°. Although the effects on the cooling system of lowering the flap are unimportant, it is interesting to note that the useful front pressure range was reduced, due to the increased upflow angle at the leading edge of the wing.

Comparisons of the pressure properties of the three ducts are given in figures 31 to 36. A definite improvement in each succeeding type of duct is quite evident.

CONCLUSIONS

A few general conclusions may be drawn from this study:

Wing ducts offer an attractive method for solving the problem of cooling engine auxiliaries inasmuch as they combine reasonable simplicity with low drag and excellent cooling characteristics.

These tests indicate that from both the standpoint of drag and pressures available in the duct entrances the upper and lower lips should be located near the plane of the wing leading edge, even though this might necessitate moving the lips outside of the wing contour. The upper lip should have a generous leading-edge radius of the same order as that of the wing leading edge in order to prevent separation or premature wing stalling at high angles of attack. Care should be exercised in the design of the

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diffuser to avoid separation. Turning vanes should be used if the air is to be turned through large angles.

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REFERENCES

1. Biermann, David, and McLellan, Charles H.: Wind-Tunnel Investigation of Rectangular Air-Duct Entrances in the Leading Edge of an NACA 23018 Wing. NACA confidential report, 1940.

2. Patterson, G. N.: Modern Diffuser Design. Aircraft Engineering, vol. X, no. 115, Sept. 1938, pp. 267-273.

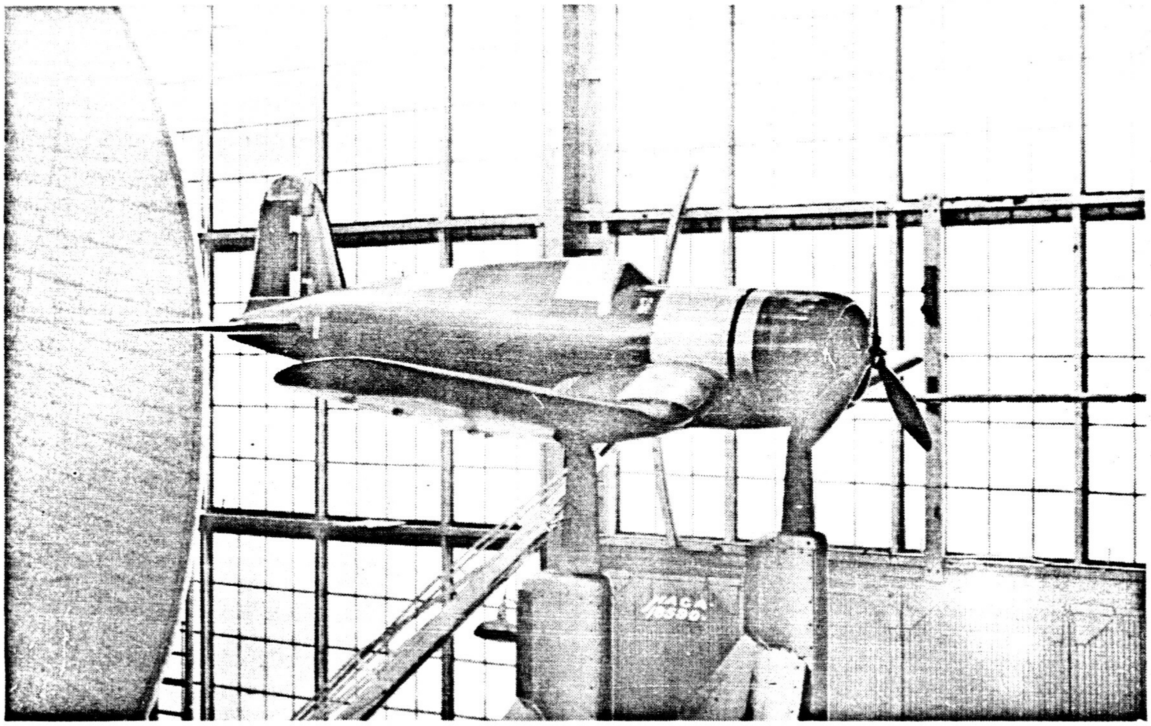

Figure 1.- Model with final modified wing ducts.

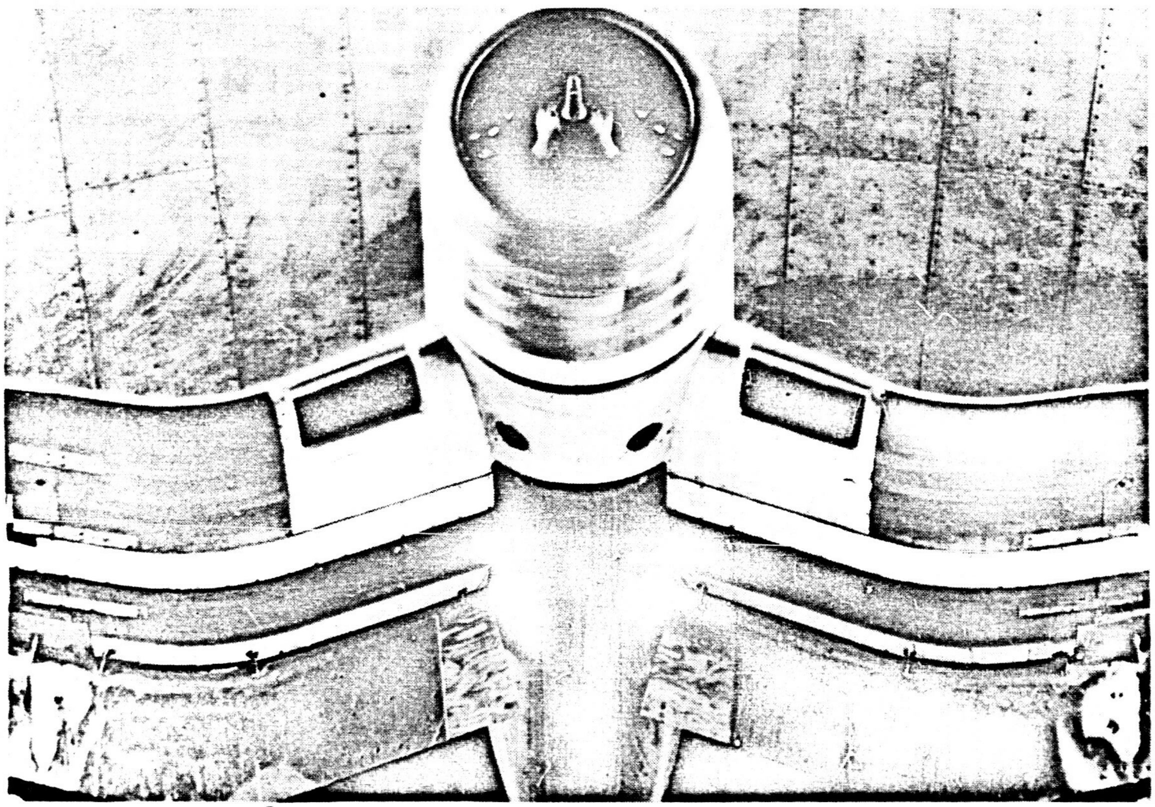

Figure 2.- Original wing ducts.

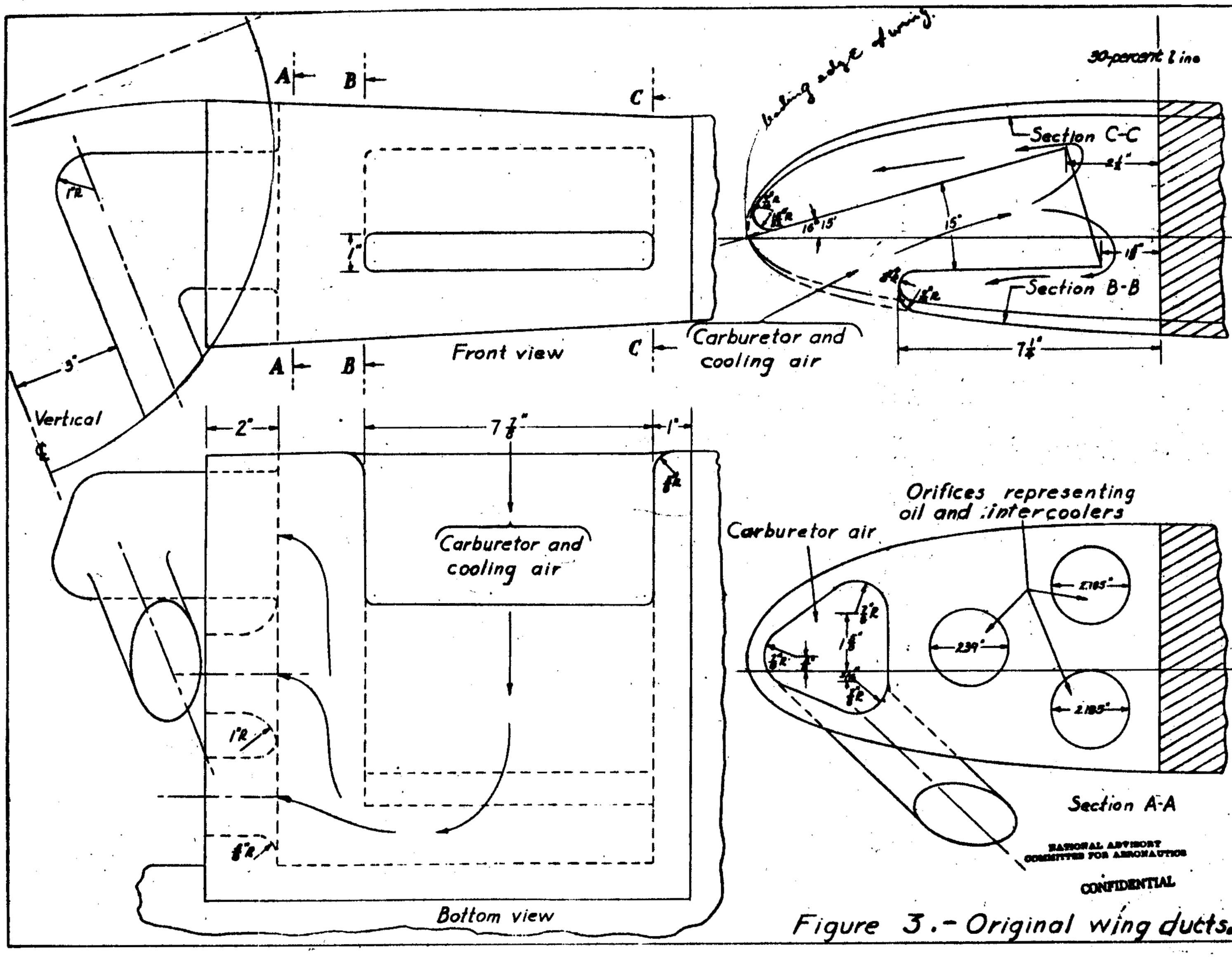

Figure 3.- Original wing ducts.

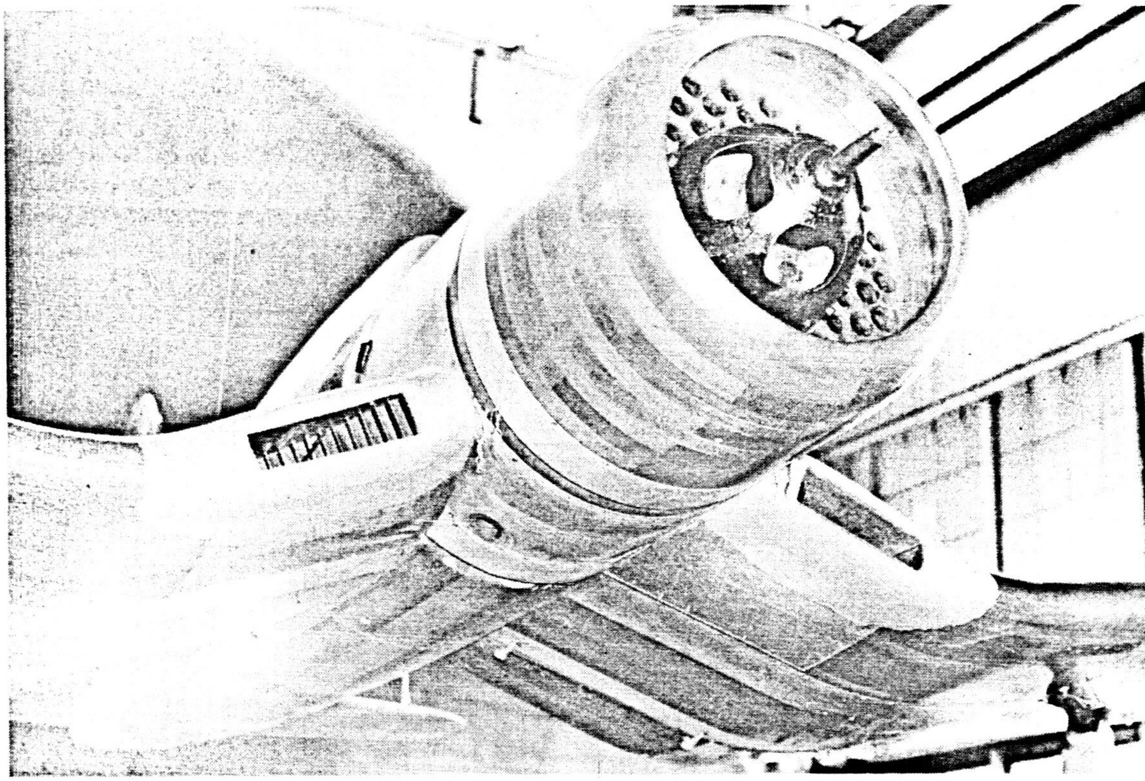

Figure 4.- First modified ducts.

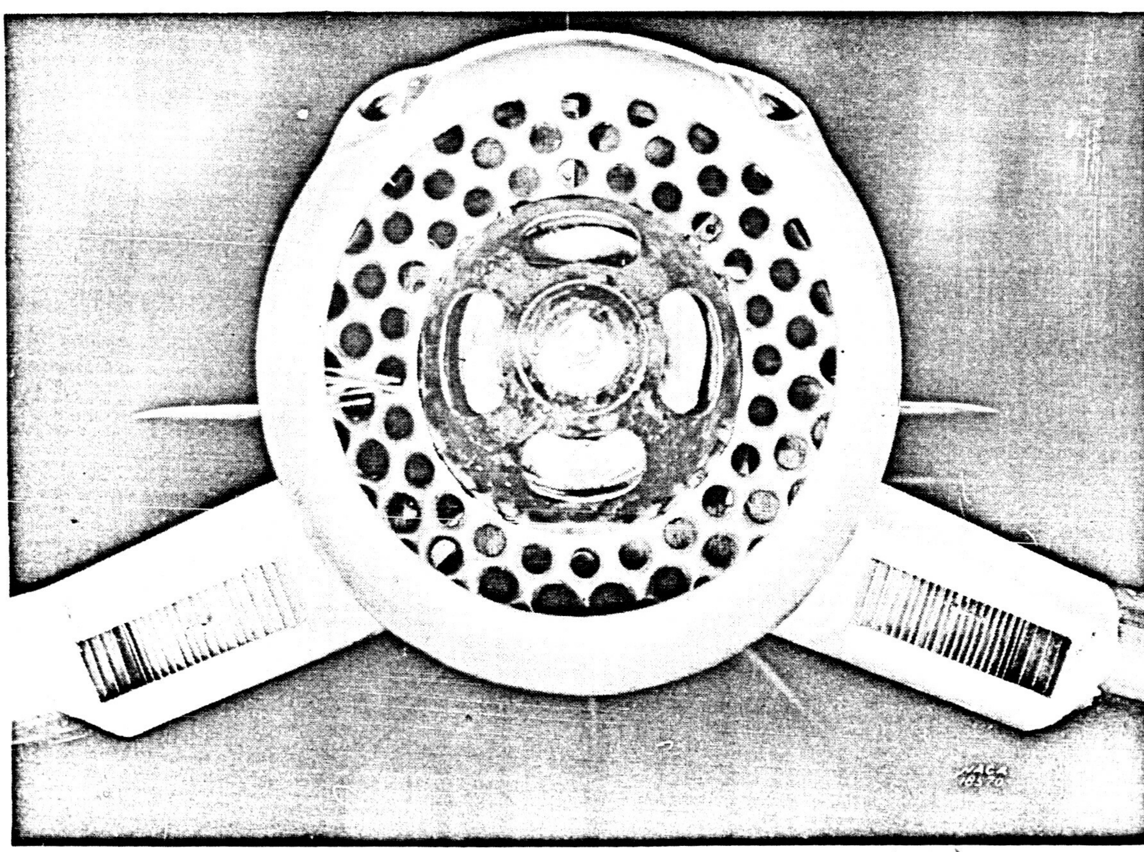

Figure 6.- Final modified ducts.

$\frac{K_L}{K_{nose}}$ ~22%

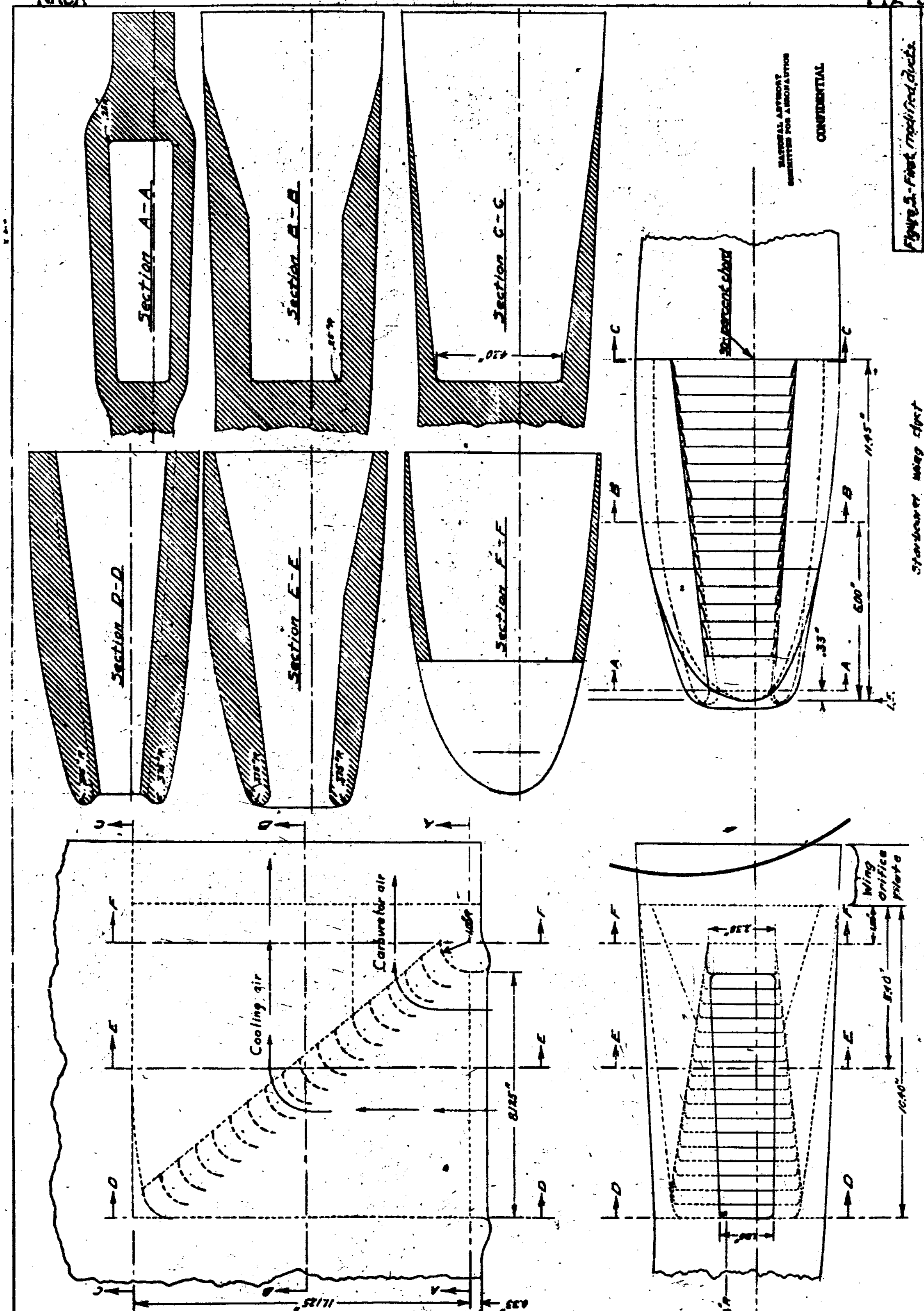

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Figure 5.-First modified ducts.

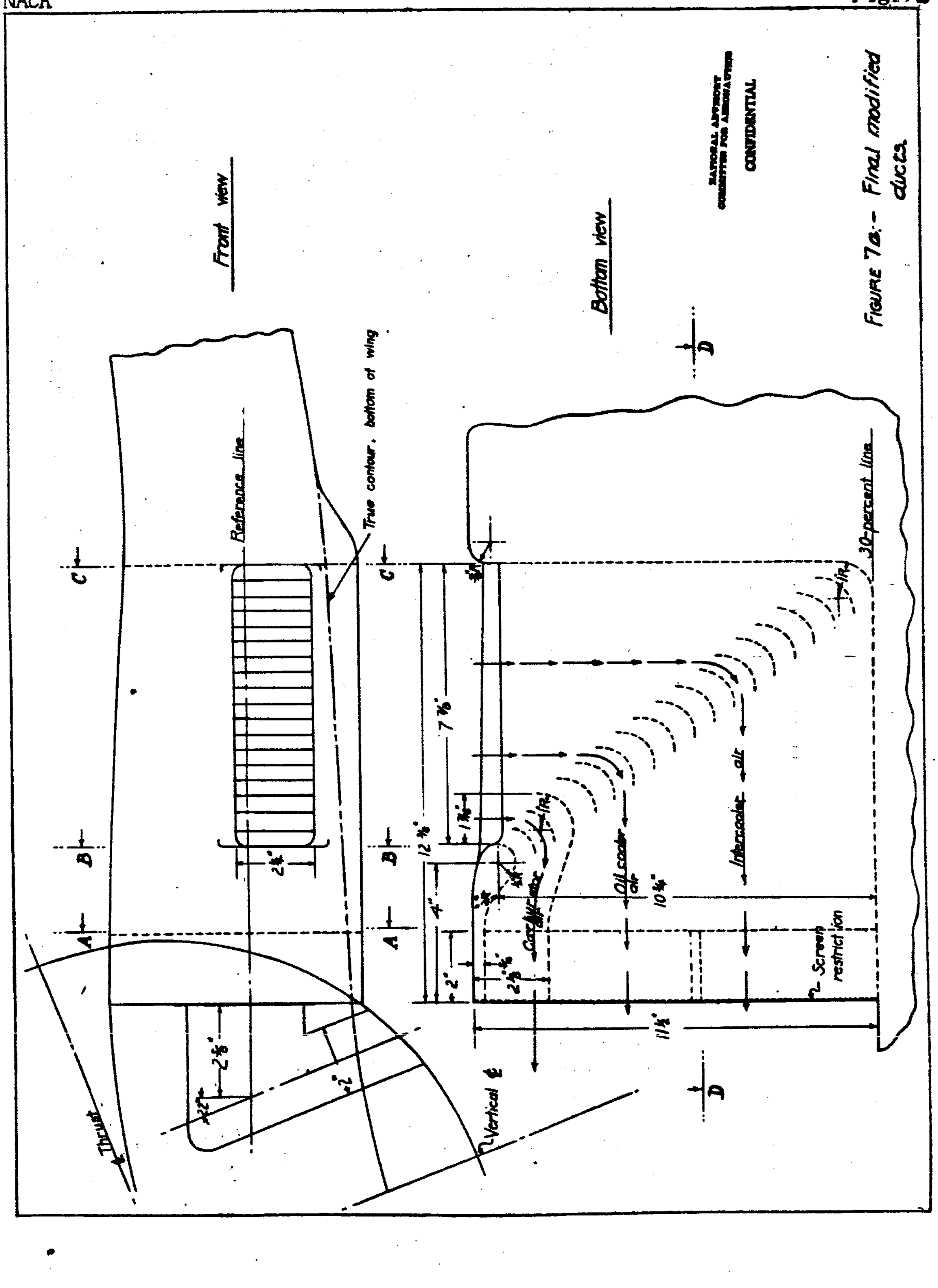
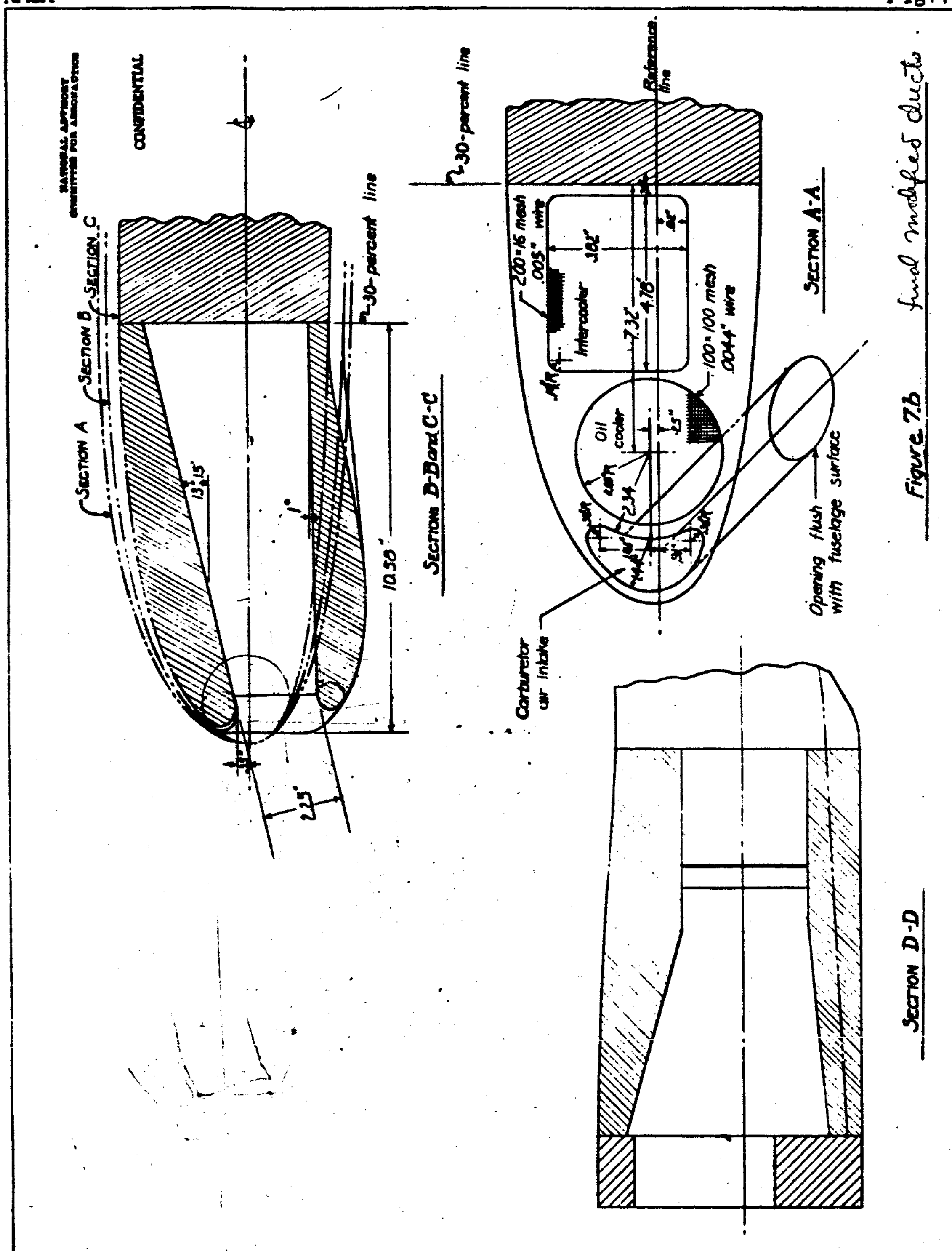


FIGURE 7a:- Final modified ducts.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Section A
Section B
Section C
30-percent line
Sections B-B and C-C
10.50"
13°15'
1°
2.25"
Reference line
200×16 mesh .005" wire
Intercooler
3.02"
7.32"
4.78"
100×100 mesh .0044" wire
Oil cooler
2.34
Section A-A
Opening flush with fuselage surface
Carburetor air inlet
Section D-D
final modified duct

Figure 7b

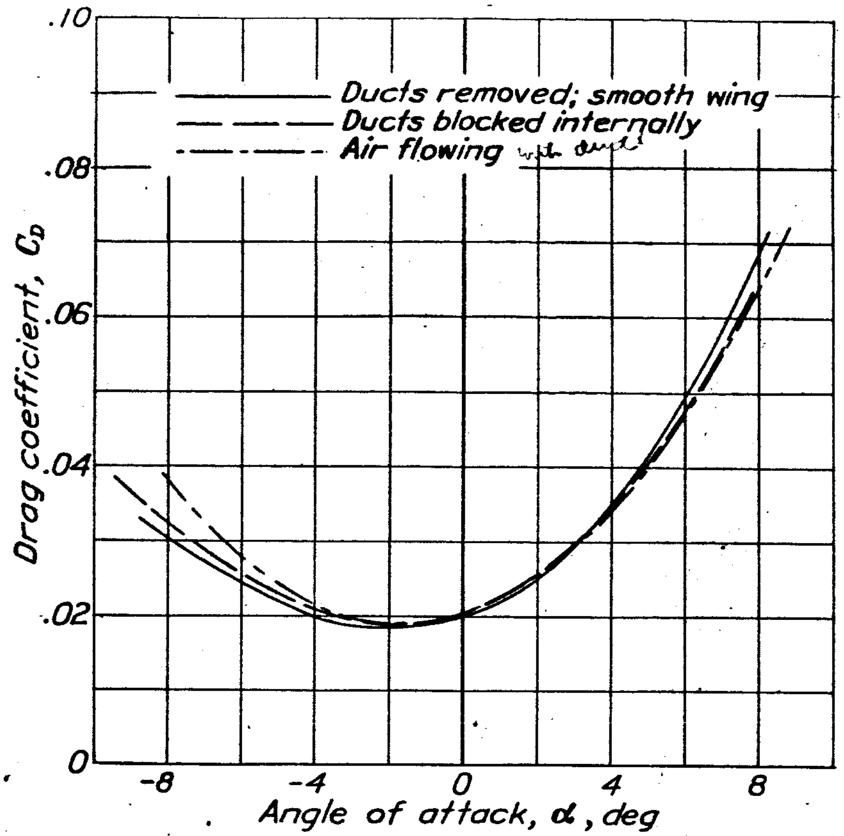

Figure 10.- Effect of the final modified ducts on the drag of the model. Duct entrance, 36 sq. inches; exit flap, 0°.

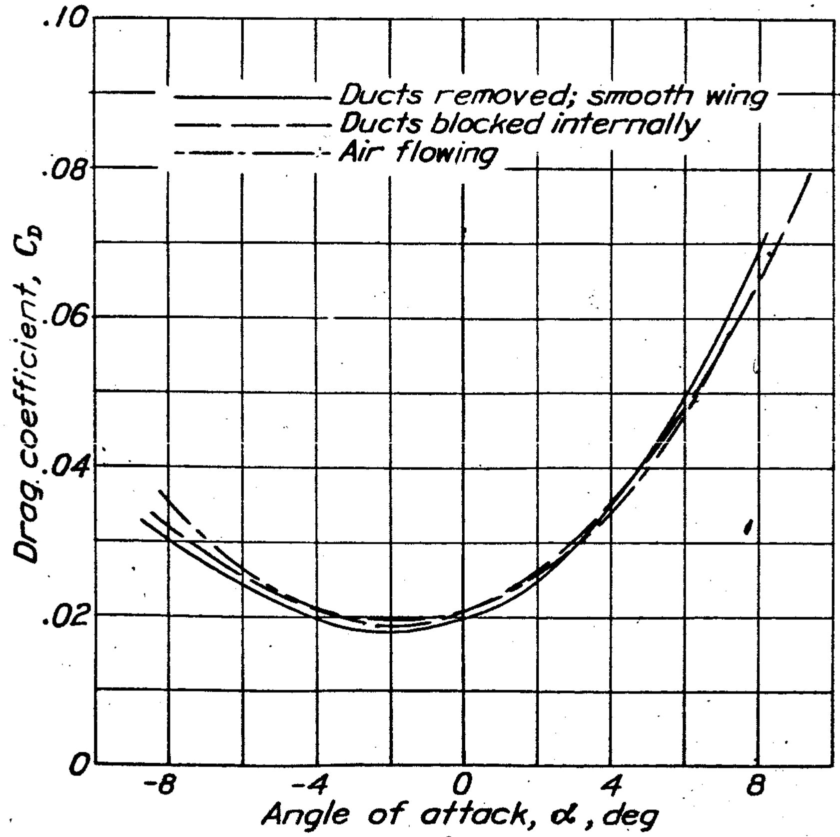

Figure 11.- Effect of the final modified ducts on the drag of the model. Duct entrance, 28.6 sq. inches; exit flap, 0°.

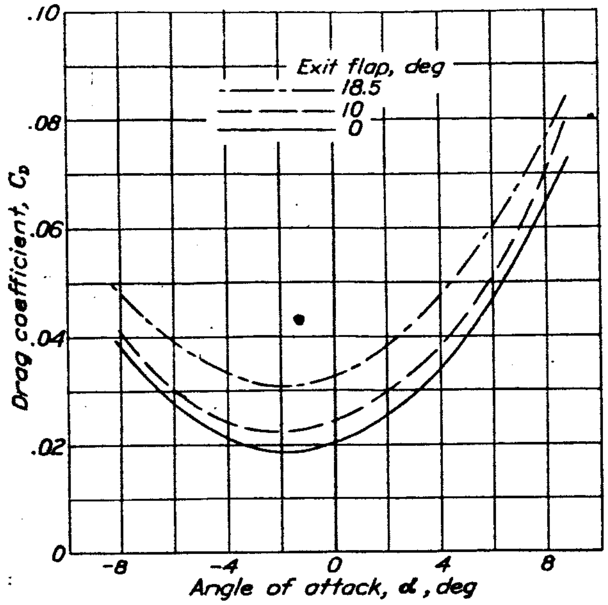

Figure 12.- Effect of the final modified ducts on the drag of the model for three exit flaps. Duct entrance, 36 sq in.

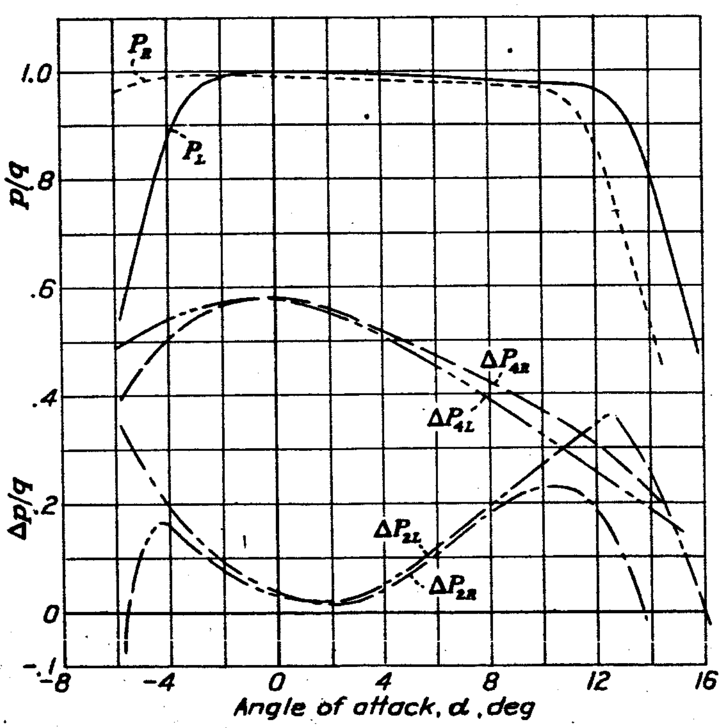

Figure 20.-

Final modified ducts. Duct entrance, 36 sq in.; exit flap, 10°; controls neutral.

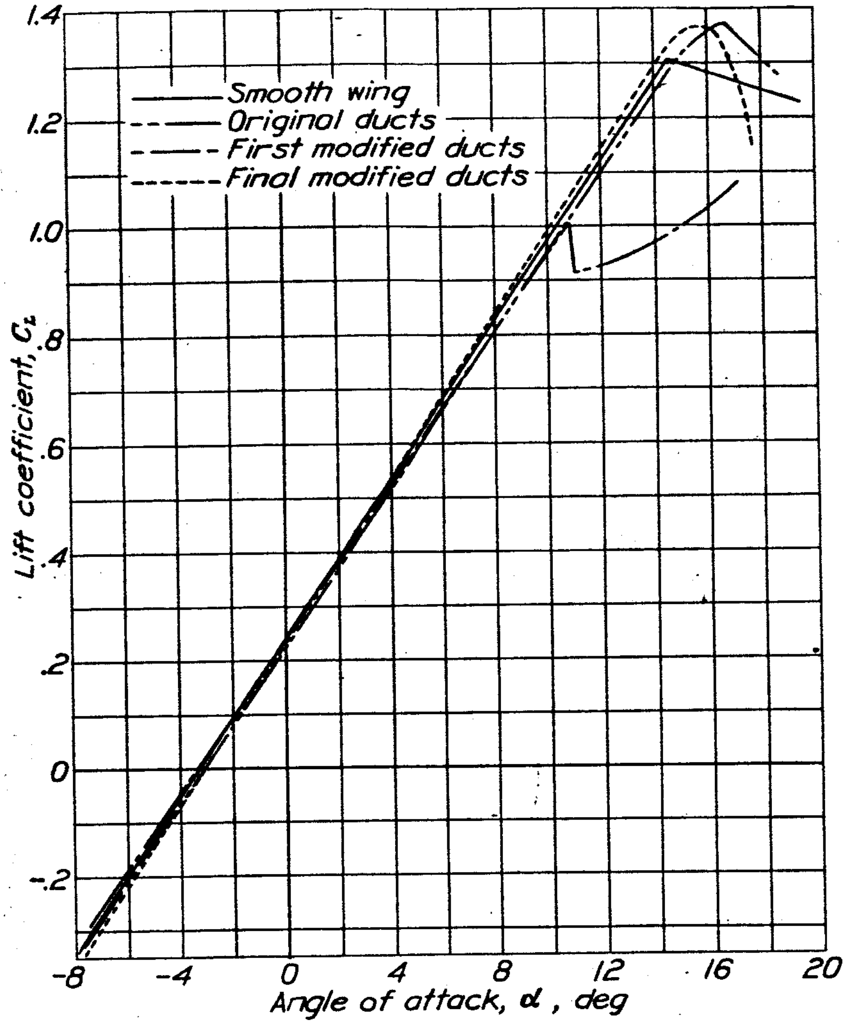

Figure 13.- Influence of ducts on lift.

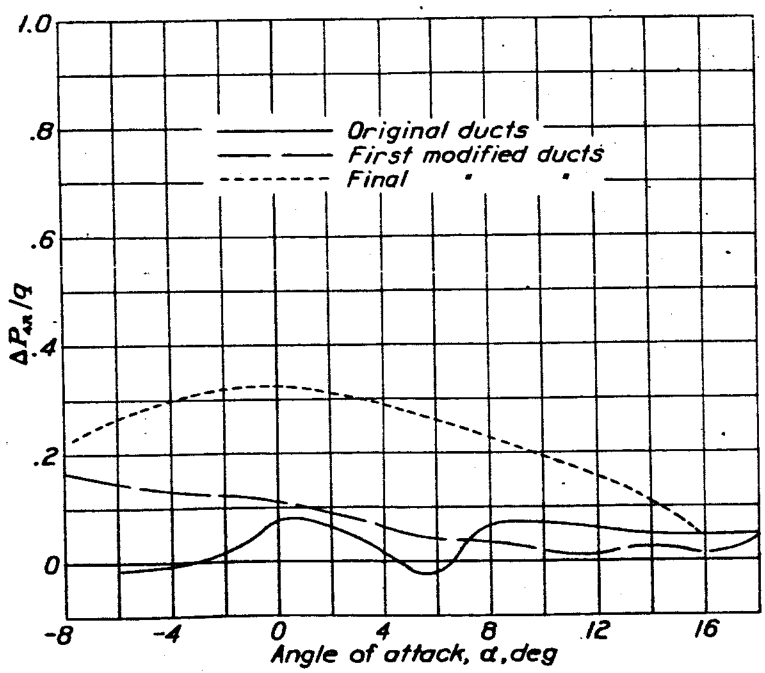

Figure 35.- Comparison of pressure drop across oil cooler and intercooler in starboard duct. Exit flap, 0°.

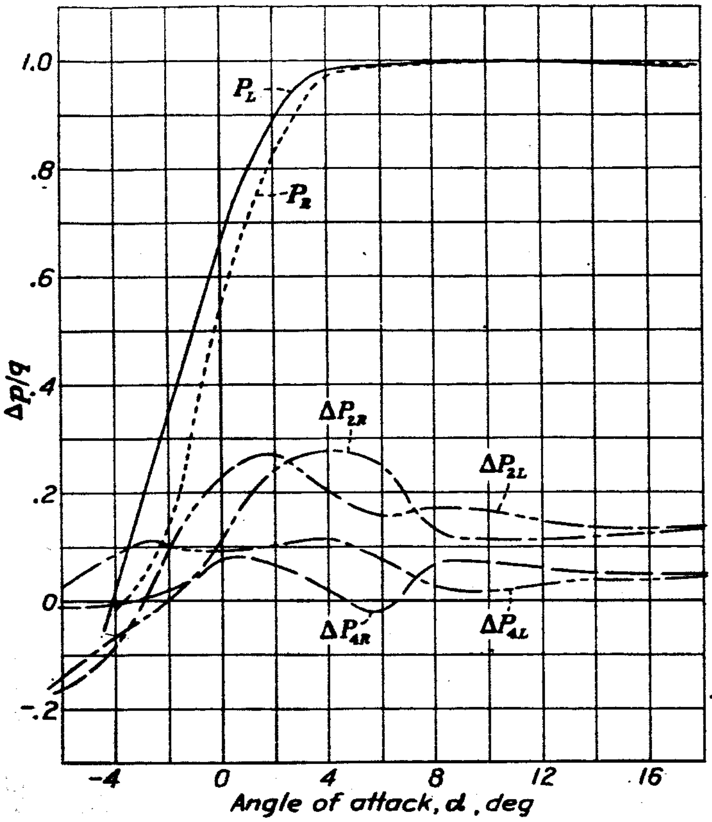

Figure 14.- Original ducts. Exit flap, 0°.

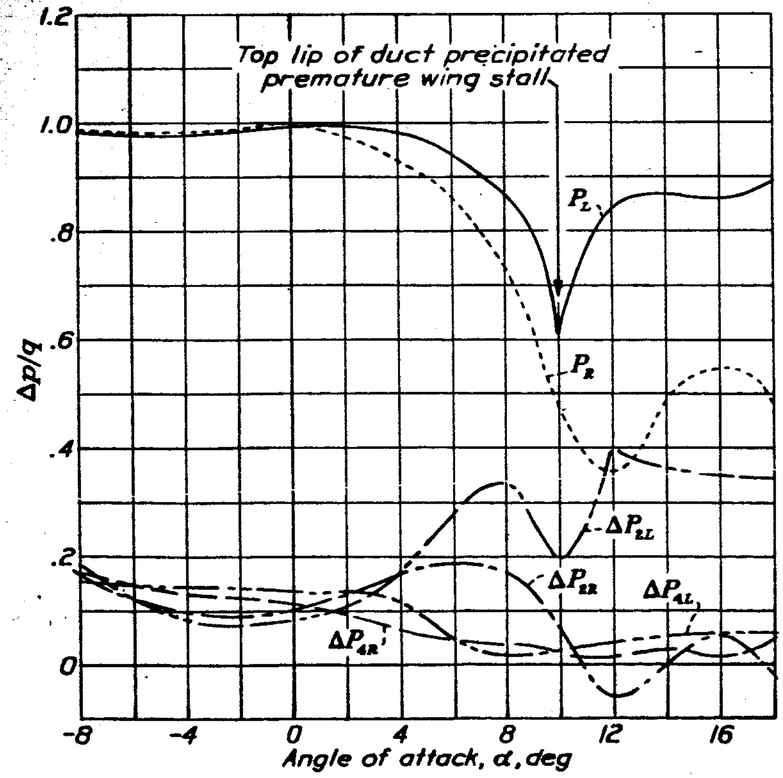

Figure 16.- First modified ducts. Exit flap, 0°.

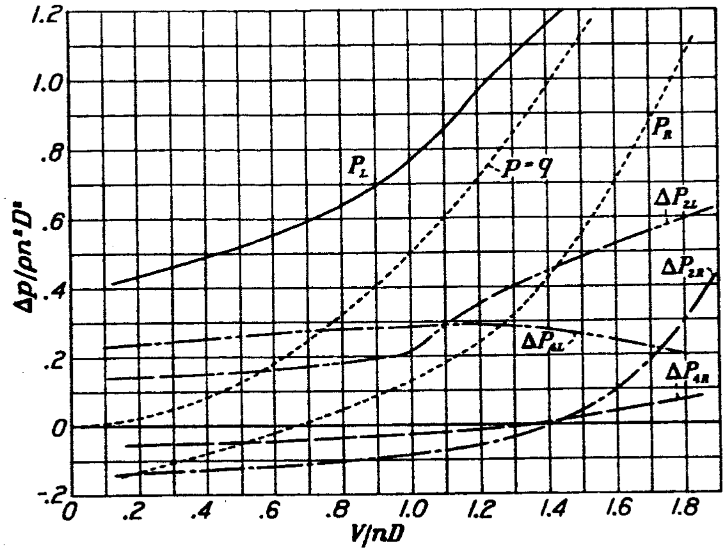

Figure 15.- Original ducts. Exit flap, 0°; α , 0°; β , 40°.

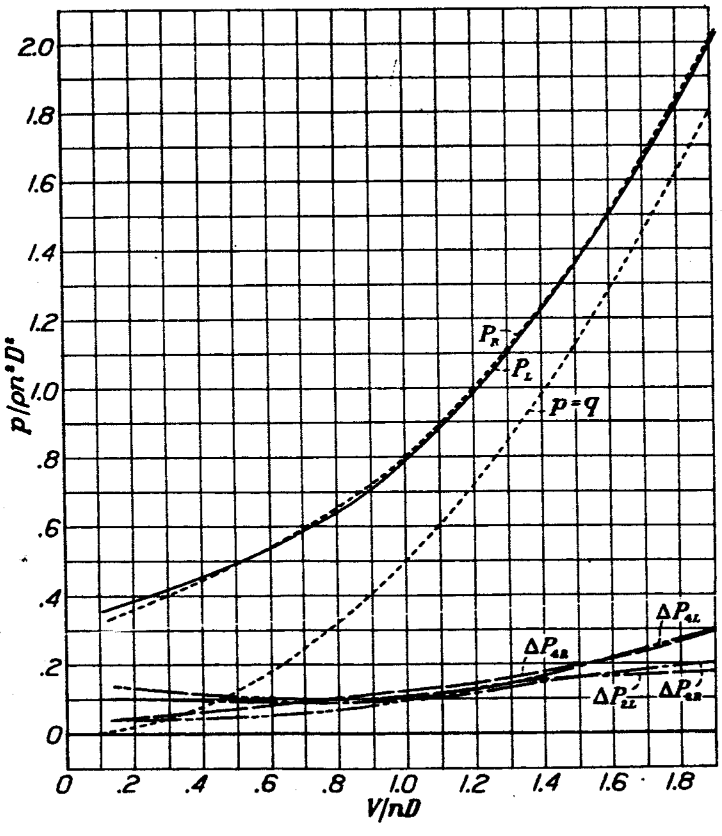

Figure 17.- First modified ducts. Exit flap, 0°, α , 0°; β = 40°.

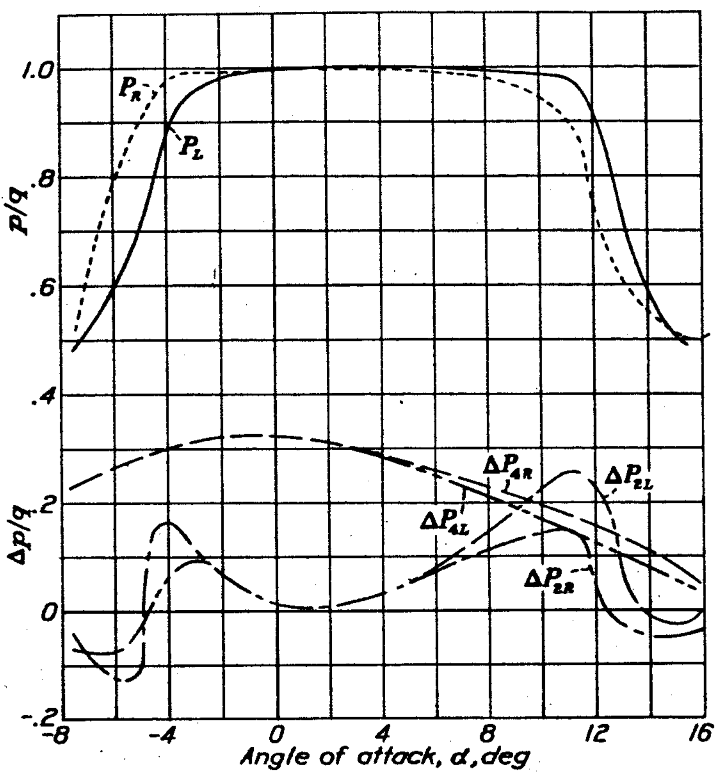

Figure 18.- Final modified ducts. Duct entrance, 36 sq in.; exit flap, 0°.

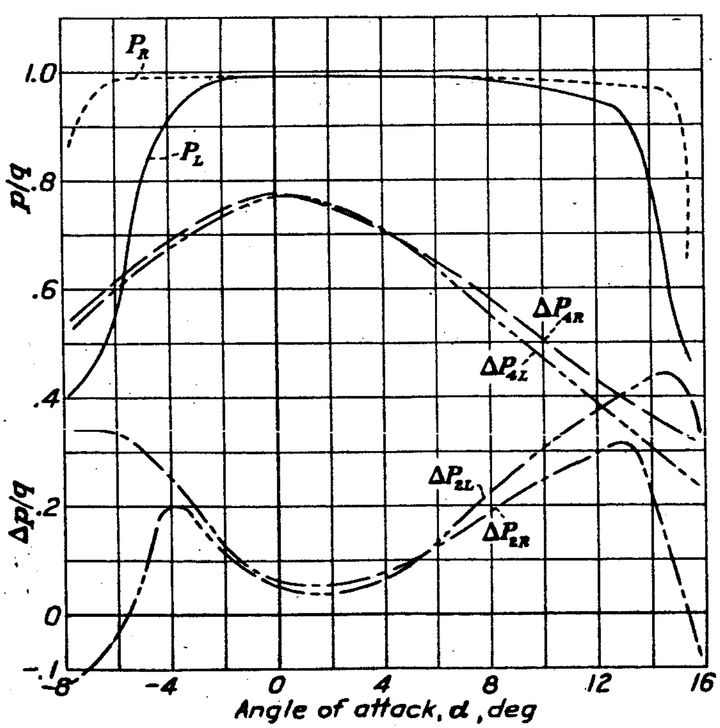

Figure 22.- Final modified ducts. Duct entrance, 36 sq in.; exit flap, 18.6°.

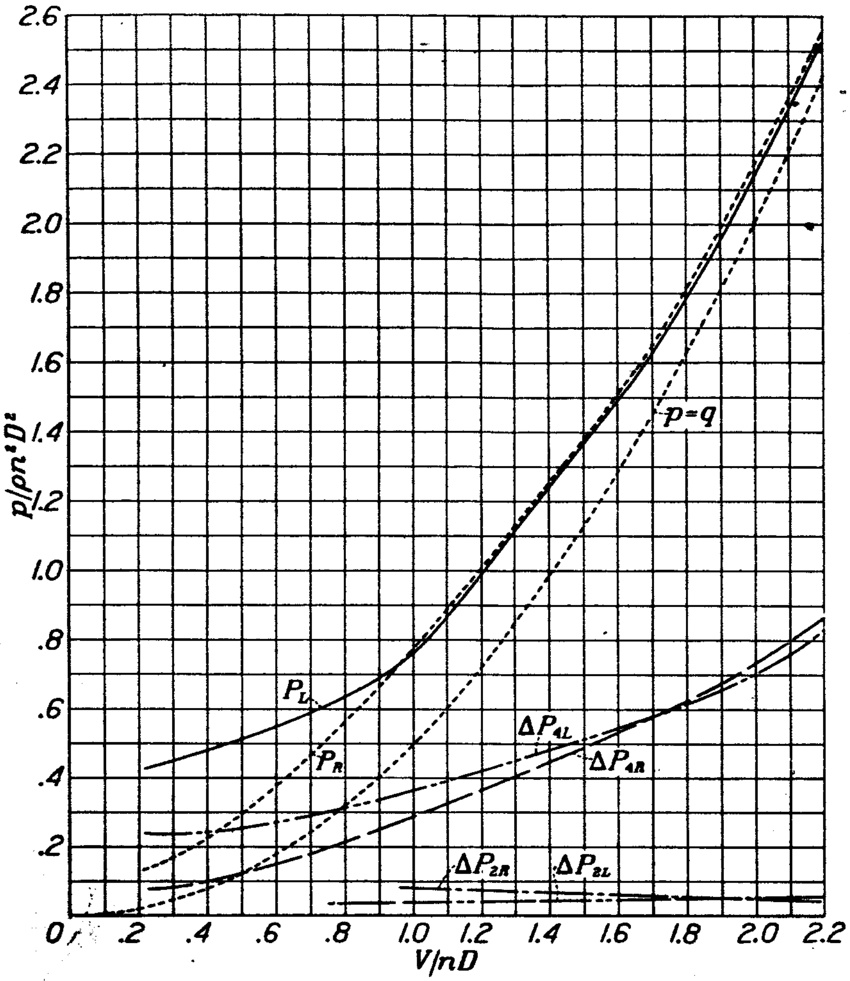

Figure 19.- Final modified ducts. Duct entrance, 36 sq in.; exit flap, 0°; α , 0°; β , 40°, controls neutral.

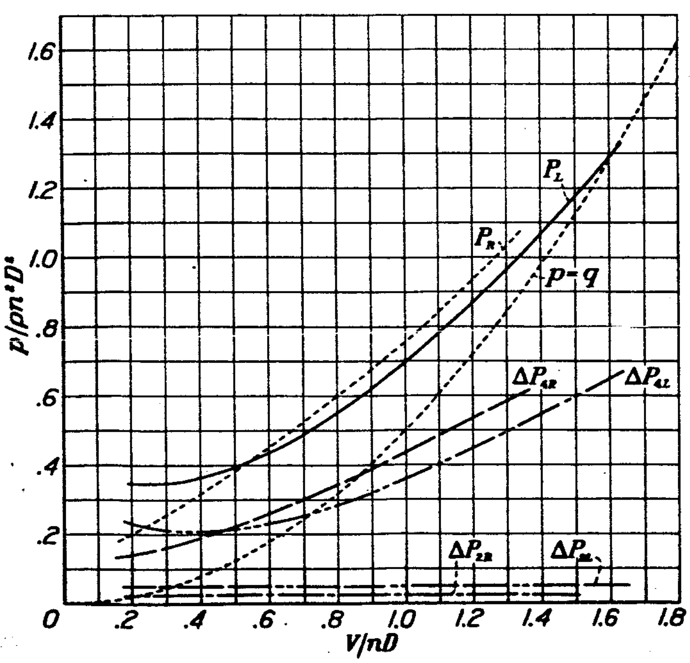

Figure 21.- Final modified ducts. Duct entrance, 36 sq in.; exit flap, 10°; α , 5°; β , 30°; controls neutral.

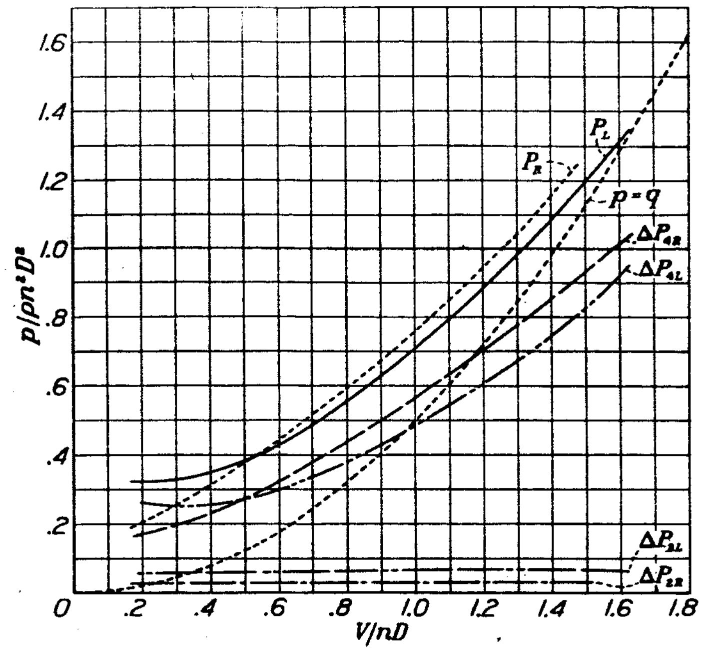

Figure 23.- Final modified ducts. Duct entrance, 36 sq in.; exit flap, 18.5°; α, 5°; β = 30°.

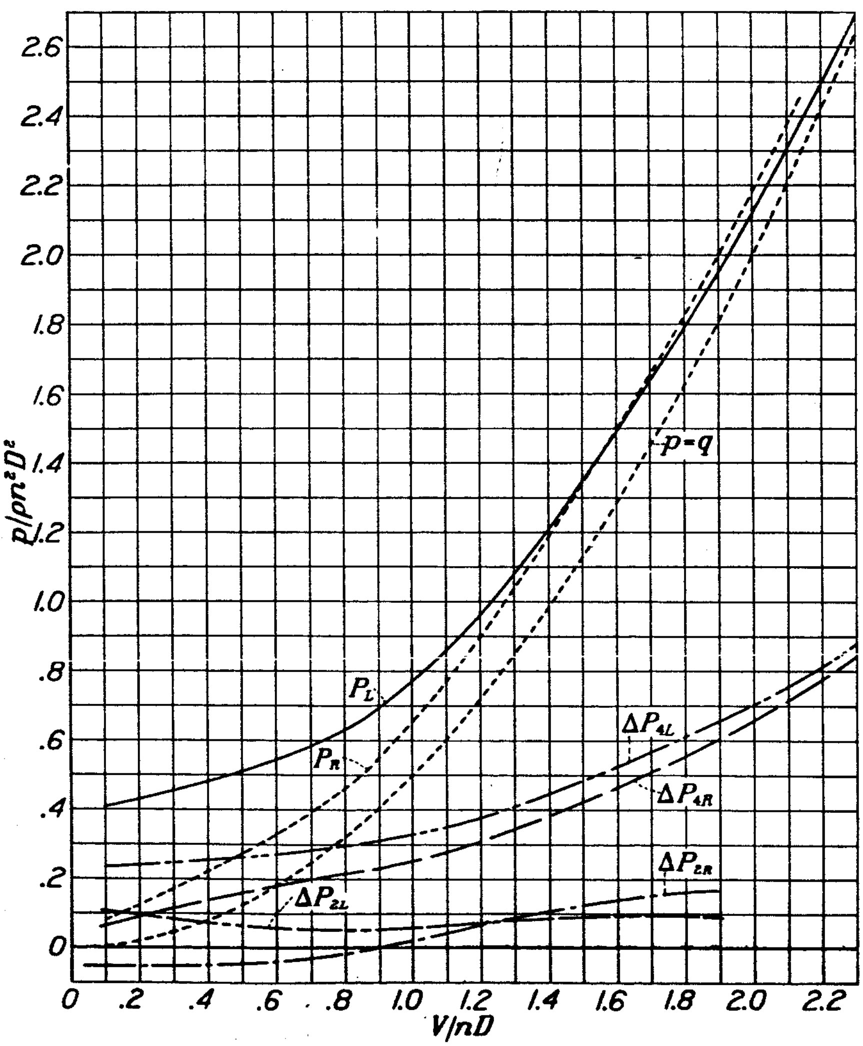

Figure 25.- Final modified ducts. Duct entrance, 28.6 sq in.; exit flap, 0°; α, 0°; β, 40°; controls neutral.

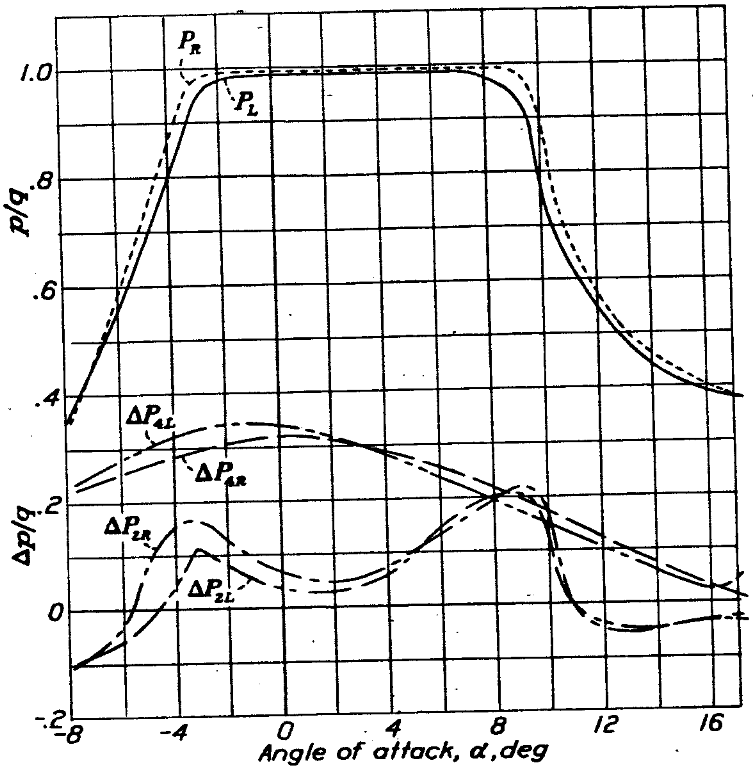

Figure 24.- Final modified ducts. Duct entrance 28.6 sq in.; exit flap, 0°; controls neutral.

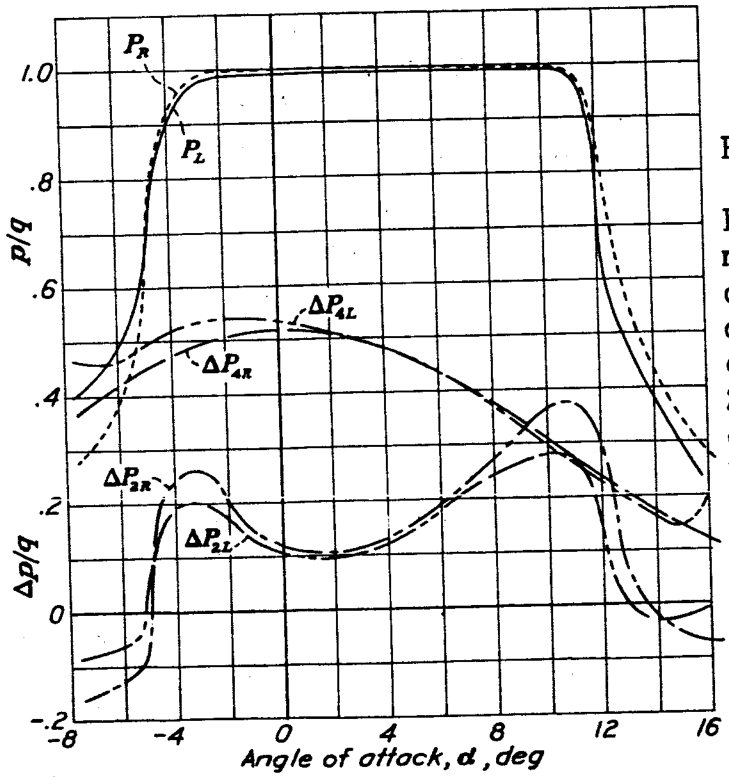

Figure 26.- Final modified ducts, duct entrance, 28.6 sq in.; exit flap, 10°; controls neutral.

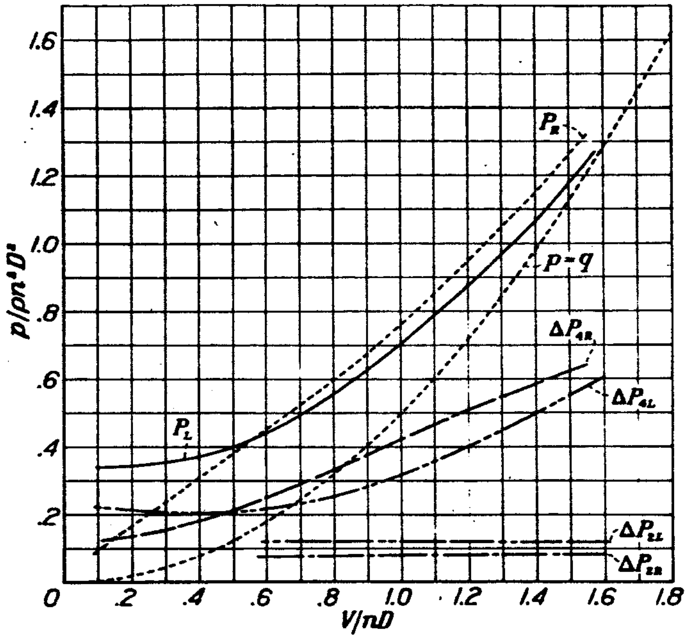

Figure 27.- Final modified ducts. Duct entrance, 28.6 sq in.; exit flap, 10°; α , 5°; β , 30°; controls neutral.

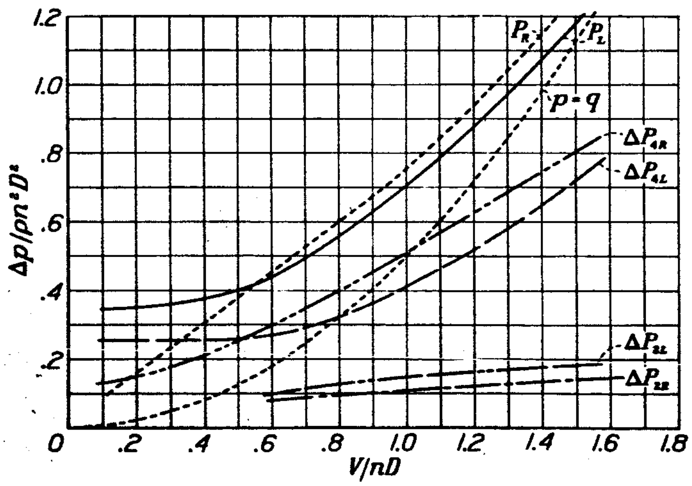

Figure 29.- Final modified ducts. Duct entrance, 28.6 sq in.; exit flap, 18.5°; α , 5°; β , 30°; controls neutral.

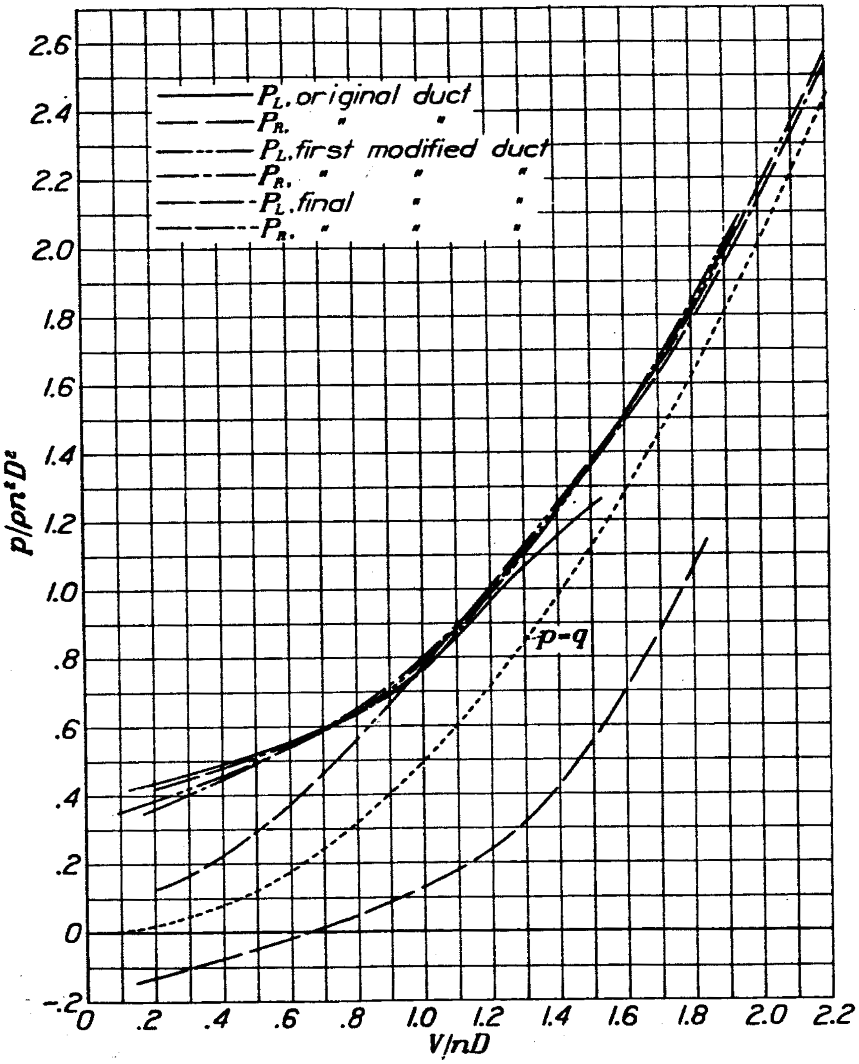

Figure 32.- Comparison of total pressure available at the duct entrance with propeller operating. Exit flap, 0°; α, 0°; β, 40°.

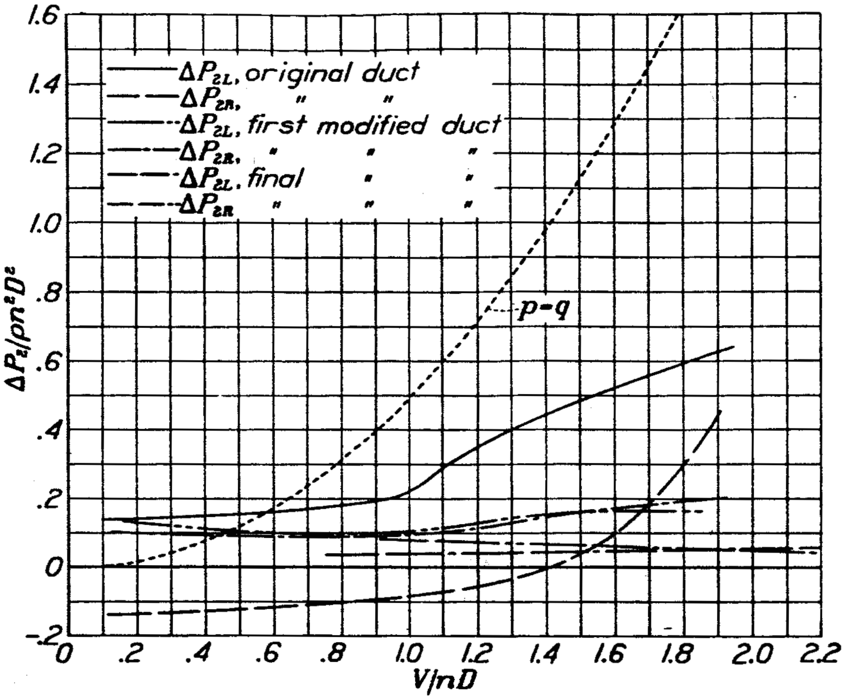

Figure 34.- Comparison of diffuser pressure losses. Exit flap, 0°; α, 0°; β, 40°.

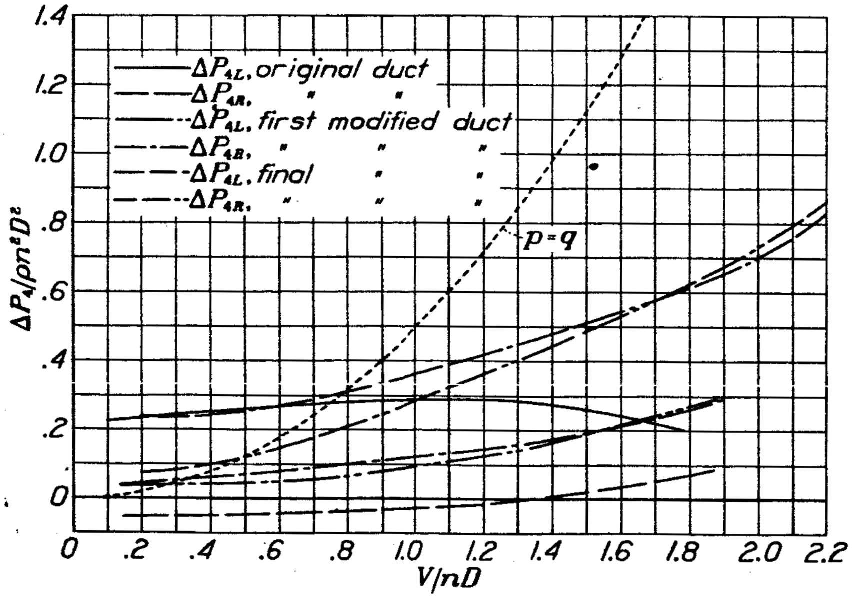

Figure 36.- Comparison of pressure drop across intercoolers and oil coolers. Exit flap, 0°; α, 0°; β, 40°.